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High-resolution trade-off analysis and optimization of ecosystem services and disservices in agricultural landscapes

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ABSTRACT

Agricultural land management often involves trade-offs between ecosystem services (ES) and disservices (EDS). Balancing these trade-offs to achieve low-impact production of agricultural commodities requires rigorous approaches for quantifying and optimizing ES and EDS, reconciling biophysical constraints and different management objectives. In this study, we demonstrate a high-resolution spatially-explicit analysis of ES and EDS trade-offs for irrigated corn production systems in the South Platte River Basin, Colorado, USA, as a case study. The analysis integrated a biogeochemical model (DayCent) with optimization algorithms to assess trade-offs between multiple ES and EDS indicators, including net primary production, soil organic carbon, water use, nitrogen leaching, and greenhouse gas emissions. Our results show a large fraction of total potential system productivity (up to 21 Mg ha^{-1} year^{-1}) can be realized at minimal ecosystem impacts through careful land management decisions. Our analysis also explores how different land management objectives imply different landscape configurations.

1. Introduction

Although the provision of food and fiber has always been the primary objective of agricultural production, agricultural ecosystems can also be managed for other benefits such as climate mitigation, water quality improvement, and biodiversity conservation. The collection of these benefits are referred as "ecosystem services" (ES) (MA, 2005). Agricultural ecosystems are affected by a variety of human activities involving land use decisions and specific land management practices. The negative impacts of humans on these ecosystems can directly reduce productivity (e.g. reduced soil fertility and loss of habitat for biodiversity conservation) or impose detrimental off-site effects on other ecosystems and human society such as ground water pollution from nutrient leaching, pesticide poisoning of non-target species, and increased greenhouse gas (GHG) emissions. These negative impacts are known as "ecosystem disservices" (EDS) (Zhang et al., 2007). Due to resource limitations (e.g., land, water, nutrients, technology, and labor) in agricultural production, there are often trade-offs between and among ecosystem services/disservices (hereafter referred as ES-EDS trade-offs). For instance, increasing food and fiber production tends to come with higher GHG emissions and nitrogen leaching (Power, 2010). The questions of interest are "what is the magnitude of the trade-off, i.e., how much change in one ES or EDS would lead to change in other ES and/or EDS?" and "how do we optimize ES-EDS trade-offs for the most efficient agricultural production?". Answering these questions is a context-dependent exercise that necessitates quantifying agricultural ES and EDS and their spatial-temporal dynamics at different scales and levels (de Groot et al., 2010), and integrating those results with optimization procedures for trade-off analyses.

Earlier studies on ES assessments used land cover types as indicators to infer potential values of ES and EDS in different landscapes (Maynard et al., 2010; Kershner et al., 2011; Schneiders et al., 2012; Bagstad et al., 2013). Subsequently, ES-EDS trade-offs were examined using scenario analysis, which facilitates the investigation of drivers of change and the impacts of certain land use and land management options on ES and EDS indicators under specifically defined scenarios (Volk, 2013). The use of land cover types as ES indicators, while useful for the rapid and cost-effective analysis of aggregated watersheds and natural landscapes, falls short of describing the underlying ecosystem processes, the temporal and spatial dynamics of the ES and EDS provision, and the changes in ES and EDS as a function of varying external factors such as management decisions, policy, and market price (Villa

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et al., 2014). Therefore, it does not allow the finer measurements of the ES-EDS trade-off nor support the integration of optimization procedures.

Quantifying ES and EDS is a difficult task that requires thorough understanding of fundamental physical and biological processes within the ecosystem. In practice, such understanding is often challenged by limited, incomplete, and/or costly field measurements. Furthermore, ecosystem responses to external disturbances are highly heterogeneous due to variability in soils, climate, land use history, and other site-specific attributes, making interpolation between existing field trials with statistical models very difficult. More recent studies overcome these issues by using process-based models coupled with geographic information system (GIS) to quantify ES and EDS associated with variations in crop rotation schemes and management practices, in a spatially-explicit manner (Lautenbach et al., 2013; Kragt and Robertson, 2014; Balbi et al., 2015). A process-based model is the mathematical representation of the underlying processes that characterize the functioning of well-delimited biological systems (Buck-Sorlin, 2013). Models such as DAYCENT (Del Grosso et al., 2000), DNDC (Li et al., 1992), and APSIM (Keating et al., 2003) can capture the finer-scale influence of site-specific weather conditions, soil properties, crop types, cropping practices, and land use history that determine the provision of ES and EDS (Nguyen et al., 2017). Although this approach requires calibration, validation, setup, and implementation of complex dynamic models, as well as in-field expertise to carry out the analysis, it provides more insights into the fundamental physical and biological processes that determine ES and EDS, allowing a continuous feedback between decision-making and the corresponding changes in different ES and EDS at multiple spatial scales.

The use of process-based modeling approaches for ES and EDS quantification, coupled with optimization procedures (simulation-optimization) for trade-off analyses, can make decision-making in natural resource management more effective, efficient, and defensible (Volk, 2013). Process-based models can be employed for exploratory quantification of ES and EDS to investigate the potential production of an agricultural landscape based on a set of well-defined scenarios. The results can then be optimized with mathematical algorithms like the non-dominated sorting genetic algorithm (NSGA-II) (Lautenbach et al., 2013), simulated annealing (Chan et al., 2006), or goal programming (Aldea et al., 2014). ES-EDS trade-offs are often presented via simulated Pareto frontiers (also called 'production possibility frontiers'), which define the set of solutions that maximize ES while minimizing EDS given finite available resources (i.e. biophysical constraints). Decision makers can then decide on the optimal solutions on the Pareto frontier that meet their specific management objectives.

Although this simulation-optimization approach has been adopted in previous ecosystem service studies, we found that most studies focused on the aggregation of ES-EDS trade-offs at regional, national, or sub-global levels to inform strategic policy-making (e.g., Lautenbach et al., 2013; Lester et al., 2013; Kragt and Robertson, 2014; Balbi et al., 2015; Ewing and Runck, 2015; King et al., 2015; Kennedy et al., 2016). Other spatially-explicit studies zeroed in on the tactical optimizations of biofuel supply chain and/or biofuel crop production systems at coarse resolutions such as land resource unit level (5 square-mile hexagons) (Yu et al., 2014), hydrological response units (HRU) (> 204 ha) (Lautenbach et al., 2013), county-level (Tittmann et al., 2010), watershed and sub-basin level (Parish et al., 2012). Only few studies could quantify ES-EDS at finer spatial resolutions, such as field-level (Zhang et al., 2010). Besides, these studies often considered a limited number (between 1 and 4) of ES-EDS objectives to ease the optimization and visualization. Thus, there is a lack of higher-dimensional trade-off analyses at more local scales (i.e., finer spatial, temporal, and management resolutions) to inform the direct decision-makers of agricultural ecosystems (e.g., farmers, ranchers, and forest landowners) on how they could manage their farms (the principle decision unit in the agricultural landscape) for optimal ES and EDS provision. As implied by Zhang et al. (2007) and Power (2010), when it comes to ES-EDS trade-offs in spatially heterogeneous ecosystems like agriculture, the devil is really in the details.

Our study aims at demonstrating the linkages among different components, including the field-scale and detailed quantification of management-induced ES changes, the landowner's management preferences, and the multiobjective optimizations for rigorous trade-off analyses of multiple ES and EDS in agricultural ecosystems. We present this research with a case study on high-resolution quantification of ES-EDS tradeoffs and optimization of fertilizer and irrigation decisions for irrigated corn production in the South Platte River Basin, Colorado, United States. A biogeochemical model (DayCent) was employed for exploratory quantification of five ES and EDS, including biomass production, soil carbon storage, water provision, water quality, and climate regulation, at the field scale (1 ha). The model simulations considered the effects of site-specific factors such as soil properties, weather data, and historical (dated back to the 1880s) land use and current management practices on the ES and EDS quantification. The simulated outputs of ED and EDS were linked with a non-dominated sorting algorithm to construct Pareto frontiers quantifying the best possible basin-scale outcomes. We then used linear programming to identify the optimum fertilizer and irrigation rates for each land unit in the basin based on different predefined land management objectives.

2. Case study and method

2.1. Study site

Our study focused on the irrigated corn growing area in the South Platte River Basin located within north-central Colorado, USA (Fig. 1). The region is among the most productive irrigated agricultural areas in the state with a majority of fine-loamy soils, average growing season evapotranspiration of irritated corn crop of 65 cm reported by the Colorado Agricultural Meteorological Network (http://www.coagmet.com/), average growing season precipitation of 31 cm, and average minimum and maximum growing season temperature of 11.4 °C and 24.7 °C, respectively (Mesinger et al., 2006). The total area of the study region is 116,959 ha, comprising 33% of all irrigated area in the basin (CDSS, 2010).

The South Platte River Basin is facing many issues such as water pollution from excessive fertilizer run-off and large-scale diversion of limited water resources away from irrigated agriculture (dry-up) in order to meet future municipal and industrial (M&I) needs (Water Conservation Board, 2010). The South Platte agricultural area ranked first in nitrate contamination and second in phosphorus contamination among the 20 major rivers in the US (Strange et al., 1999). This is due to the basin's low capacity of contaminant dilution, which is 10 times below national average level (Mueller et al., 1995) and the lack of riparian vegetation to filter irrigation return flows and feedlot run-off (Loomis et al., 2000). According to the Colorado's Statewide Water Supply Initiative 2010 report (Water Conservation Board, 2010), under medium economic development assumptions, the population of the South Platte Basin is projected to grow from 3.5 million people in 2008 to 6.0 million people by 2050. This would result in a 136-million-cubic-meter gap in water supply for M&I uses and will likely trigger a permanent dry-up of 73,000 to 108,000 ha of irrigated farmland in the basin (Water Conservation Board, 2010). The large-scale dry-up of irrigated agriculture land will likely cause significant negative economic, social, and environmental impacts to the basin and to the whole state. These issues necessitate integrated assessments and better landscape